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Oceanography

Initiation of transform faults at rifted continental margins

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Abstract

Data from the Woodlark Basin, Gulf of Aden and NW Australia show that spreading segments nucleate en echelon in overlapping rift basins and that transform faults develop as or after spreading nucleates; typically they are not inherited from transverse rift structures. Initial spreading offsets, where present, are often non-transform. After continental break-up, spreading center segmentation is modified by ridge jumps and/or propagation. ***To cite this article: B. Taylor et al., C. R. Geoscience 341 (2008).***

Résumé

Initiation des failles transformantes au niveau des marges continentales passives. Les données recueillies au niveau du bassin de Woodlark, du Golfe d'Aden et de la marge Nord-Ouest Australienne montrent que les segments d'accrétion océanique se mettent en place en échelon au sein des bassins de rift et que les failles transformantes se développent en même temps ou juste après le début de l'accrétion océanique. Ces failles transformantes ne sont pas héritées de structures transverses du rift. Les traces de l'expansion initiale, quand elles sont présentes, sont toujours non transformantes. Après la rupture continentale, la segmentation des centres d'accrétion océanique est modifiée par des sauts et/ou des propagations de rides. ***Pour citer cet article : B. Taylor et al., C. R. Geoscience 341 (2008).***

Keywords: Transform fault; Spreading segmentation; Continental break-up; Oceanic crust; Continent-ocean boundary; Gulf of Aden; NW Australia

Mots clés : Faille transformante ; Accrétion océanique segmentée ; Cassure continentale ; Croûte océanique ; Frontière océan-continent ; Golfe d'Aden ; Nord-Ouest de l'Australie

1. Introduction

Transform faults that connect spreading centers, Wilson [37] proposed, are inherited from initial offsets formed during the break-up and subsequent drift of continents. Fracture zones, their inactive extensions, should therefore originate from, and end in, sheared segments of conjugate continental margins. Since this defining paper, there has been ongoing debate whether transform faults originate pre- or syn-rifting or even after continental break-up. Early works proposed that some fracture zones in the South Atlantic [18],

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Norwegian-Greenland Sea and off SE Australia [23] continue into the adjacent continents, suggesting their control by pre-spreading structures. Indeed, Lister et al. [23] proposed that passive margins are characterized by an orthogonal set of normal and transform faults. In contrast, based on seismic reflection studies of the East African Rifts, Gulf of Suez, and many rifted margins, Bosworth [6] and Rosendahl [27], amongst others, proposed that half graben, delimited along strike by accommodation zones, are the fundamental unit of rift architecture. Furthermore, accommodation zones are most commonly oblique features, as is well documented for the margins of the northern Red Sea [7,21], making them unlikely precursors of transform faults. In that case, transform faults would form at or after continental break-up. That would also occur where extension and differential strain at rift offsets are accommodated by magmatism rather than by faulting, as is common in back-arc basin rifts [32].

The 3-D nature of the transition from rifting to seafloor spreading is poorly known for old conjugate margins. Typically old margins are difficult to accurately reconstruct and/or sufficiently buried in sediments that their structural architecture is veiled. Insights from active continental rifts are also limited in those cases where the extension has not yet progressed to seafloor spreading. In the northern Red Sea offshore the critical evidence is obscured by the presence of thick evaporates that have prevented comprehensive mapping of the basement structures and fabrics. Although basement shear zones are observed on either side of the Red Sea, transform faults have yet to form between the spreading cells, the most developed of which (in the south) have been opening for 5 or 10 Ma. [9,10]. In contrast, transform faults are well developed in the central and eastern Gulf of Aden. There, Tamsett [28] proposed that the transform faults formed between offset, parallel rifts arranged en echelon along an initial zone of weakness. In his kinematic model, consistent with that of Wilson [37], the transforms connect the ends of offset spreading segments that nucleated within overlapping en echelon rift basins.

In this paper we present new and previously published data from the young, thinly sedimented, Woodlark Basin that reveal in detail how spreading center segmentation evolved between conjugate rifted continental margins [33,34]. We show that initial spreading offsets are commonly non-transform and that none of the transform faults developed until seafloor spreading had begun (i.e., they were not inherited from transverse rift structures). In two instances the transform faults formed before the conjugate margins were fully separated and truncated one tip of originally overlapping spreading segments or rifts. In younger examples (< 2 Ma) with offsets less than 50 km, transform faults have yet to form between overlapping spreading segments even though the continental margins are separated by oceanic crust. We show that these examples are consistent with the evidence from studies of the Gulf of Aden and NW Australia that even large-offset transform faults develop as or after spreading segments nucleate en echelon in overlapping rift basins.

2. Seafloor spreading in the Woodlark Basin

The break-up of the Papuan continent may be associated with the lateral change from subduction of the Solomon Sea Plate to the continent-arc collision that occurs beyond the western convergence of the Trobriand and New Britain Trenches (Fig. 1), an inference consistent with analogies to 3-D lab experiments and the separation of Arabia from Africa [3]. Seafloor spreading initiated in the eastern Woodlark Basin by ~6 Ma (Chron 3A.1; [30,36]) and, together with the prior rifting, allowed an increased rate of subduction and rotation of the Solomon Sea plate into the New Britain Trench. Spreading propagated west in a stair-step, discontinuous fashion at an average rate of 14 cm/yr, splitting the formerly contiguous Woodlark and Pocklington Rises [29,34].

The Miocene-Recent Trobriand volcanic arc and trench terminate east of 153°E where the boundary between the Woodlark Rise and the Solomon Sea Basin is a transform margin (Figs. 1 and 2). Thus, the (eastern) Woodlark Basin did not originate as a back-arc basin [36]. West of 153°E, however, spreading propagated approximately along the Trobriand arc volcanic front, producing inherently asymmetric conjugate passive margins, with a cool and wet Neogene fore-arc to the north and a thick orogenic crust to the south [31]. The greater Woodlark Basin depths and Bouguer gravity anomalies (by ~500 m and 25 mGal, respectively) east versus west of Moresby Transform (154.2°E) have been interpreted to result from rift-induced secondary mantle convection producing thicker oceanic crust in the west, but not in the east where the continental margin crust and lithosphere apparently are substantially thinner [24]. Although the seismically active, right-lateral strike-slip fault continues across the Woodlark Rise to form a triple junction at the graben ahead of the

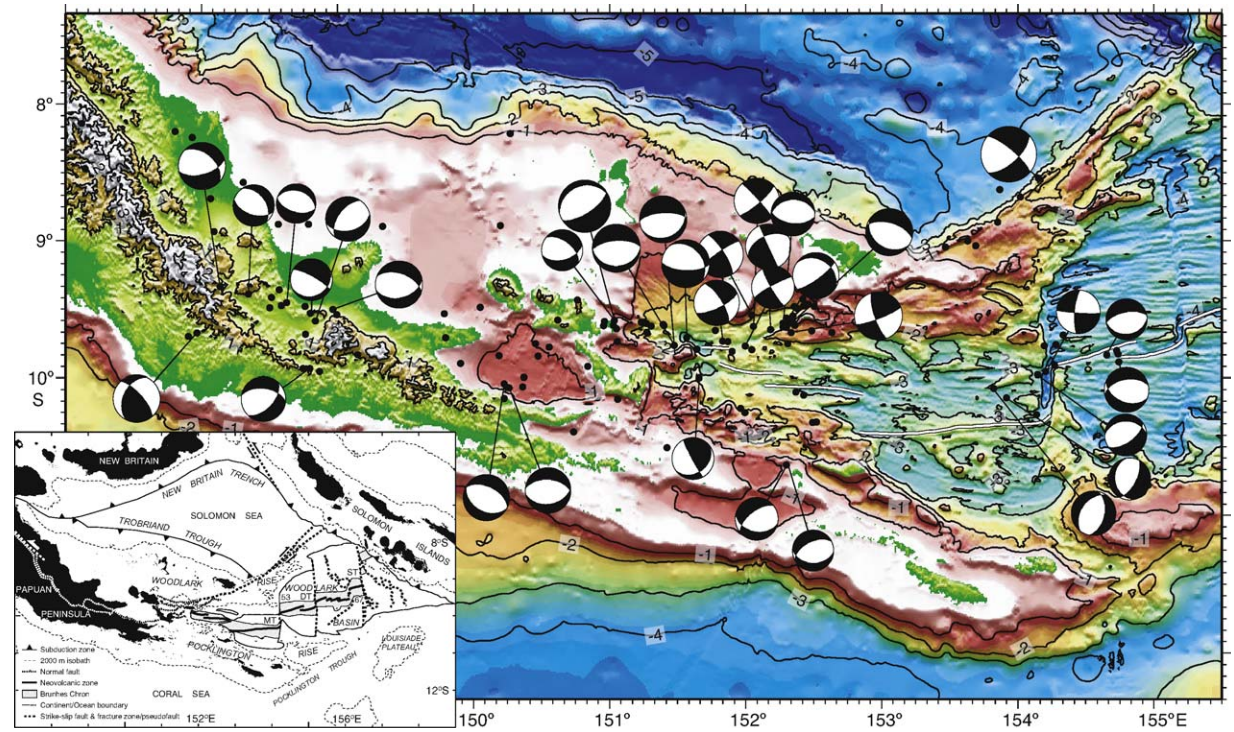

Fig. 1. Sunlit topography and bathymetry of the Papuan Peninsula and Woodlark Basin region, showing epicenters and focal mechanisms from Taylor and Huchon [31] after Abers et al. [1]. Thin double lines locate the spreading axes and kilometer labels define the bathymetry color palette used in this and subsequent figures. Inset: major physiographic features and active plate boundaries of the Woodlark Basin region. The stippled area encloses oceanic crust formed during the Brunhes Chron at spreading rates labeled in mm/yr. MT, DT and ST = Moresby, Davies and Simbo transform faults and fracture zones, respectively.

Fig. 1. Carte topographique et bathymétrique de la Péninsule de Papouasie et de la région du bassin de Woodlark montrant les épicentres et les mécanismes au foyer, de Taylor et Huchon [31], d'après Abers et al. [1]. Les fines doubles lignes localisent les axes d'expansion et les repères kilométriques définissent la palette de couleurs bathymétriques utilisée dans cette figure et dans les suivantes. Encart : traits physiographiques majeurs et frontières de plaques actives de la région du bassin de Woodlark. La zone ombrée indique la croûte océanique formée durant le Chron de Brunhes, aux taux d'expansion figurés en mm par an. MT, DT et ST = failles transformantes et zones de fracture de Moresby, Davies et Simbo, respectivement.

current spreading tip (Fig. 1), this is likely a recent development and a triple junction was not characteristic of the evolution of the rifted margins further east.

The Woodlark Basin presents several advantages compared to other basins for understanding continental break-up and the origin of oceanic ridge segmentation [33,34]. Significantly:

- the seafloor fabric and rift/ridge segmentation are revealed because of the young age and thin sediment cover (Figs. 2 and 3);
- there is a clear record of magnetic anomalies, without marginal magnetic quiet zones (Figs. 2–4);
- the basin reconstructions back to the time of break-up are tightly constrained, with ambiguities no greater than a few kilometers (Fig. 4).

Furthermore in October–November 2004, we completed the swath bathymetry, acoustic imagery, magnetic and gravity coverage of the eastern edges and margins of the Woodlark Basin on R/V Kilo Moana cruise KM0418, making it the first ocean basin to be so completely surveyed. For the purposes of this study concerned with conjugate margin evolution, we mainly present the marine geophysical data west of 155.5°E where both margins are preserved (i.e., west of where the northern margin has been subducted, Fig. 1).

Several primary characteristics of seafloor spreading in the Woodlark Basin have been described previously and are immediately apparent from inspection of Figs. 1–4:

- spreading rates significantly increase to the east, implying an opening pole nearby to the west [19,34];

- recently (~80 ka, within the Brunhes Chron), spreading reoriented and ridge segmentation changed [18];
- the continent-ocean boundary (COB) is sharp, not a broad transition, with seafloor fabric and magnetic anomalies parallel to it in some segments, but discordant in others [33];
- in the western basin, transform faults have yet to form even though the continental margins east of the spreading tip are separated by oceanic crust [33,34].

3. Initiation of transform faults in the Woodlark Basin

Seafloor spreading in the Woodlark Basin is segmented by several transform and non-transform offsets. As previously shown for the Moresby Transform and the western Woodlark Basin [33,34], all of the initial spreading offsets there are non-transform and none of the transform faults developed until seafloor spreading had begun. The lack of transform offsets and fracture zones in the western basin (between segments 1a, 1b, 1c and 2) is evidenced by the lack of north-south structures in the bathymetry and acoustic imagery (Fig. 2). The Brunhes Chron magnetization boundary (Fig. 1) shows that the same was true at 0.78 Ma: prior to the ~80 ka reorientation of spreading axes, segments 1 and 2 were overlapping propagating ridges, with a thin sliver of rifted continental crust rotated in between (Fig. 2). In contrast, the boundary between the western and eastern basins (i.e., between spreading segments 2 and 3) occurs at the Moresby Transform Fault (Figs. 2 and 3). But there also the transform fault developed after overlapping seafloor spreading segments were established.

As shown by the data in Fig. 3 and the reconstruction in Taylor et al. [34], spreading segment 2 nucleated at 1.9–2.0 Ma (just prior to magnetic anomaly 2) and segment 3 ceased propagating westward by 1.8 Ma. The overlapping spreading segments were separated by rifted continental crust prior to the formation of the Moresby Transform at ~1.5 Ma. In the process of linking the two spreading segments, the then ~70-km-offset Moresby Transform truncated the eastern tip of segment 2.

The left panel of Fig. 3 depicts a generalized evolutionary model of a transform fault and fracture zone derived from these data. It ignores the details of successive ridge jumps evidenced in the adjacent panel by dual magnetic anomalies 2 and 2A both on the northern side of segment 3. (1) A propagating spreading segment overlaps with an offset region of focused rifting. (2) The overlap continues after a spreading center nucleates within the rift basin. (3) A transform fault initiates by cutting through stretched continental crust to link the two spreading segments, truncating the former tip of one segment. Note that fracture zone traces do not extend into the continental margin; they terminate within oceanic crust in the south and at the COB in the north. While it is obvious from the data of Fig. 3 that the Moresby fracture zone trace does not extend southward into the continental margin, its trace west of the formerly overlapping oceanic tip is obscured in the bathymetry fabric by overshooting spreading ridges and in the magnetization by the alignment of anomalies Jaramillo (J) and 2.

Fig. 4 shows our new bathymetry and magnetization data surrounding the Davies fracture zone (~155.2°E, Fig. 2) reconstructed to 2.6 Ma, at the end of the Gauss Chron and magnetic anomaly 2A. At that time, spreading segments 3 and 4 jumped to the south, leaving most of both magnetic anomaly 2A north of the spreading axis (Figs. 2 and 4). Previous southward ridge jumps of segment 4 had created a non-transform offset within an originally continuous spreading segment 5. Subsequently, segment 4 overlapped with, and propagated eastwards at the expense of segment 5 [34].

Our first order interpretation of the magnetization and seafloor fabric is that continental break-up for spreading segments 3 and 4–5 slightly predates the Gauss Chron (3.6 Ma), occurring outside of magnetic anomaly 2A, with segment 3 nucleating just after segment 4–5 (Figs. 2 and 4). In detail, however, there is a region of seafloor with apparent oceanic crustal fabric to the south of segment 4 (bounded by the dashed yellow line in Fig. 4). This may be an early cell of organized spreading that has no northern conjugate. In either case, the Davies Transform formed by cutting through rifted continental crust before the conjugate margins were fully separated to link already nucleated spreading segments that were offset en echelon. Note that the northern rift basin adjacent to the COB continues to the west beyond the Davies fracture zone. Like Moresby, the Davies fracture zone does not extend beyond the oceanic crust into transverse structures or across rift zones of the conjugate margins.

4. Alula-Fartak and Cape Range Fracture Zones (CRFZ)

Of the many other transform faults that could be considered in relation to their rifted margins, we

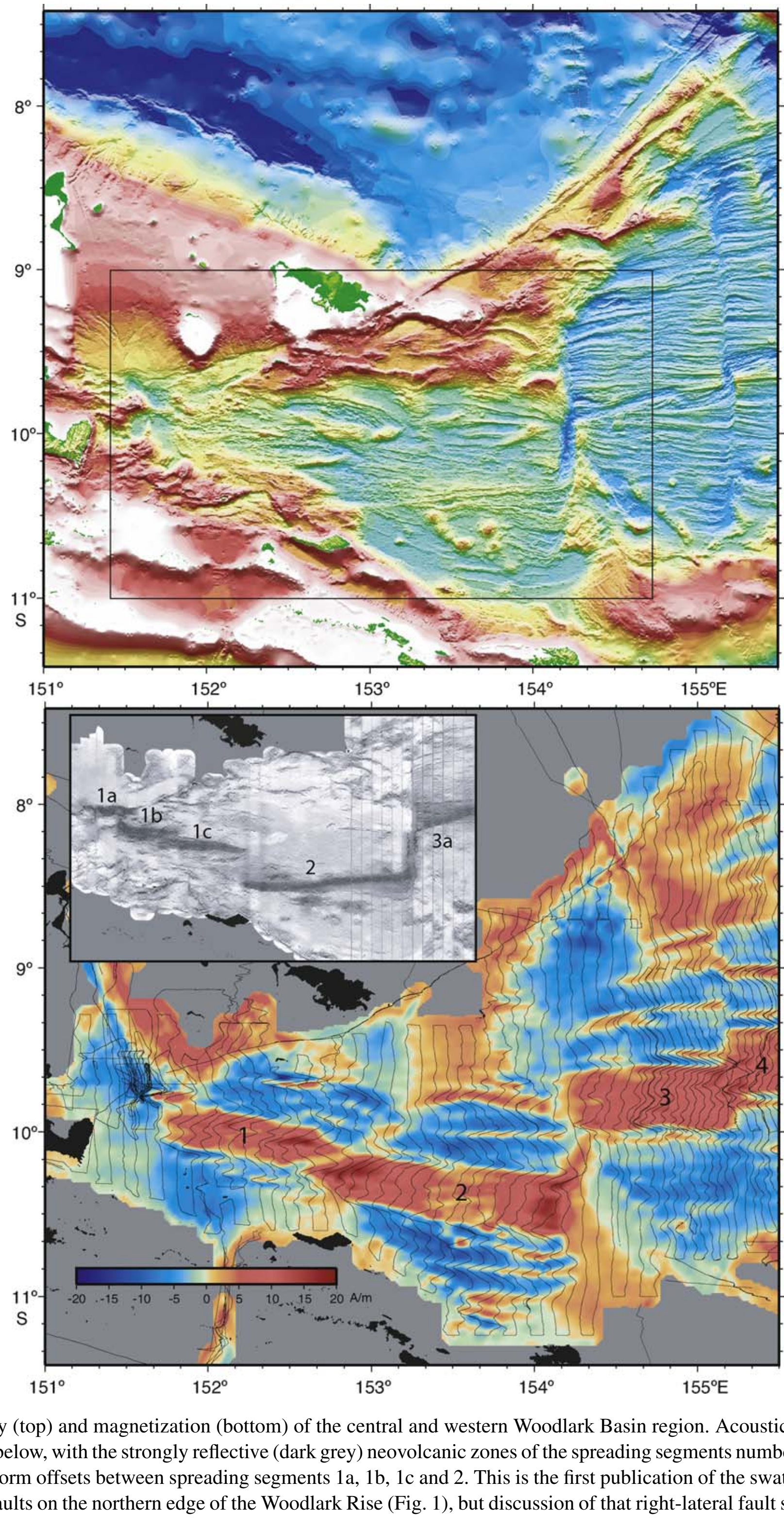

Fig. 2. Sunlit bathymetry (top) and magnetization (bottom) of the central and western Woodlark Basin region. Acoustic imagery of the top boxed area is shown in an inset below, with the strongly reflective (dark grey) neovolcanic zones of the spreading segments numbered following Taylor et al. [34]. Note the non-transform offsets between spreading segments 1a, 1b, 1c and 2. This is the first publication of the swath bathymetry of the active NE-trending transform faults on the northern edge of the Woodlark Rise (Fig. 1), but discussion of that right-lateral fault system will be presented in another publication.

Fig. 2. Bathymétrie (en haut) et aimantation (en bas) des régions centrale et occidentale du bassin de Woodlark. L'imagerie acoustique du cadre indiqué sur la figure du haut est reportée en encart sur la figure du bas, avec les zones néovolcaniques (gris foncé) très réflectives des segments en

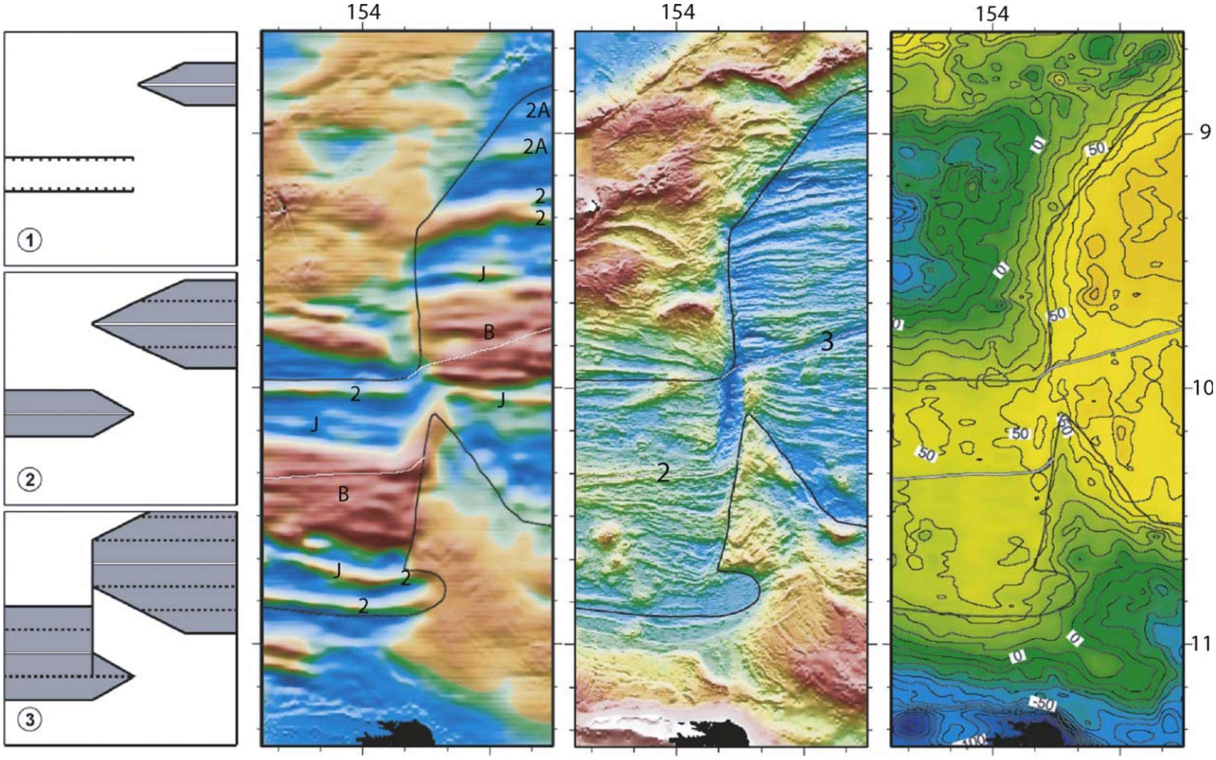

Fig. 3. Three panels (from right to left) show Bouguer gravity (contoured every 10 mGal and labeled every 50 mGal), sunlit bathymetry (with spreading segments 2 and 3 labeled), and magnetization (with lineations labeled for Brunhes (B), Jaramillo (J), anomaly 2 and 2A), respectively, of the Moresby Transform and its conjugate margins, with black line showing continent-ocean boundary [34]. The left panel depicts a derived but generalized evolutionary model of a transform fault and fracture zone whose traces do not extend into the continental margin (white region). It ignores the details of successive ridge jumps evidenced in the adjacent panel by dual magnetic anomalies 2 and 2A both on the northern side of the eastern spreading axis. (1) A propagating spreading segment (grey) overlaps with an offset region of focused rifting (barbed lines). (2) The overlap continues after a spreading center nucleates within the rift basin. (3) A transform fault initiates by cutting through stretched continental crust to link the two spreading segments, truncating the former tip of one segment.

Fig. 3. Les trois panneaux (de droite à gauche) illustrent les anomalies gravimétriques de Bouguer (avec des contours tous les 10 mGal labélisés tous les 50 mGal), la bathymétrie (les segments d'accrétion océanique 2 et 3 sont indiqués) et l'aimantation (avec les linéations indiquées (B) pour Brunhes, (J) pour Jaramillo et les anomalies 2 et 2A) pour la faille transformante de Moresby et ses marges conjuguées, avec une ligne noire montrant la limite continent-océan (Taylor et al. [34]). Le panneau de gauche décrit un modèle généralisé d'évolution d'une faille transformante et d'une zone de fracture dont les traces ne s'étendent dans la marge continentale (zone blanche) ; ce modèle ignore les détails des sauts successifs de ride mis en évidence dans le panneau adjacent par la dualité des anomalies magnétiques 2 et 2A. (1) Un segment propagateur d'accrétion (gris) recouvre une région décalée de la zone de *rifting* (lignes barbelées). (2) Le recouvrement se poursuit après qu'un centre d'accrétion s'est mis en place dans le bassin de rift. (3) Une faille transformante commence à se constituer en coupant à travers la croûte continentale étirée, pour relier les deux segments d'accrétion, tronquant l'extrémité antérieure d'un des segments.

briefly discuss two with contrasting characteristics: the ~200-km offset Alula-Fartak Fracture Zone in the Gulf of Aden and the ~400-km long CRFZ that separates the Exmouth Plateau from the Cuvier Basin off NW Australia. We do not consider highly oblique opening systems such as in the Gulf of California.

The 025°–030° opening direction of the Gulf of Aden is ~45° oblique to its 070°–075° trend. Mesozoic NW-WNW-trending rift basins with very large overlaps, associated with the break-up of Gondwanaland and following the Najd trend of the Precambrian basement, were reactivated in en echelon overlapping syn-rift basins (35 Ma-Miocene) that preceded break-up

expansion numérotés selon Taylor et al. [34]. Noter les décalages non transformants entre les segments 1a, 1b, 1c et 2. Cela est la première publication sur les données bathymétriques « swath » des failles transformantes orientées nord-est sur la bordure nord de la crête de Woodlark (Fig. 1) ; cependant la discussion à propos de ce système de faille latéral fera l'objet d'une autre publication.

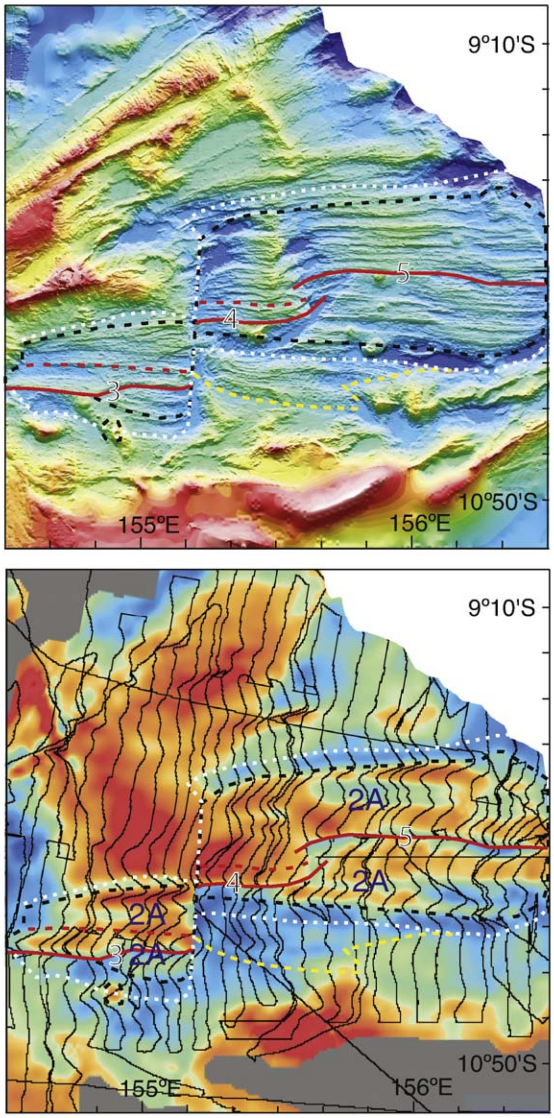

Fig. 4. Sunlit bathymetry (top), magnetization and magnetic anomaly profiles (bottom), of Woodlark Basin spreading segments 3, 4 and 5 reconstructed to 2.6 Ma. Red line locates the spreading axes, dashed red line the axes prior to a ridge jump. Dashed black lines bound crust formed during the Gauss Chron (magnetic anomaly 2A). White dashed lines locate the continent-ocean boundary, yellow dashed lines show an alternative interpretation in the south (see text for discussion). Note that the Davies fracture zone trace ($\sim$155.2°E) does not extend into the conjugate rifted continental margins and that the northern rift basin adjacent to the continent-ocean boundary extends beyond the fracture zone.

Fig. 4. Carte bathymétrique (en haut) et carte d'aimantation avec profils d'anomalie magnétique (en bas), des segments d'accrétion 3, 4 et 5 du bassin de Woodlark, reconstitués à 2,6 Ma. La ligne rouge localise les axes d'expansion et la ligne rouge en tirets localise les axes antérieurs à un saut de ride. Les lignes noires en tirets circonscrivent la croûte formée pendant le Chron Gauss (anomalie magnétique 2A). Les lignes blanches en tirets localisent la limite océan-continent, les lignes jaunes en tirets montrent une interprétation alternative au sud (voir le texte pour la discussion). À noter que la trace de la zone de fracture de Davies ($\sim$ 155,2° Est) ne s'étend pas jusqu'aux marges continentales conjuguées et que le bassin de rift nord, adjacent à la limite océan-continent, s'étend au-delà de la zone de fracture.

in the Gulf of Aden (e.g., [5,8,14,25]). Separating the Aden and Sheba Ridges, Alula-Fartak is the largest offset transform fault and fracture zone in the Gulf. Yet there are no strike-slip faults onshore in the projection of the Alula-Fartak fracture zone, only WNW-trending normal faults (Fig. 5; [11,14]). The structural and marine geophysical data clearly show that the Alula-Fartak transform fault formed after rifting, transecting across the middle of the pre-existing Qamar-Gardafui rift basin as well as the bordering Fartak-Alula horst high [4,11].

Despite this recognition, the same authors draw transfer zones orthogonal to rift structures in the conjugate margins between the Alula-Fartak and Socotra fracture zones [11,12,22]. They recognize that their interpreted lack of sigmoidal faults similar to those on the adjacent land areas may be due to the orientation and spacing of their survey lines. In fact, there is little if any evidence for orthogonal transfer structures, as their additional data have since shown [2]. Note that:

- the modern Socotra Transform Fault formed by spreading reorganization within the oceanic domain (it did not initiate at the margins and thus is not shown in the reconstruction in Fig. 5; [12,22];
- the N30°E Jabal Qarabiyan normal fault along strike from the northern Socotra Fracture Zone exhibits no strike-slip component [16] indicating that, although appropriately orientated, this transverse structure was not a transcurrent fault during rifting;
- the fracture zone to the east of the Socotra Fracture Zone terminates in structures parallel to the north coast of Socotra and to the conjugate (Al Hallaniyah) islands east of the Hasik Basin;
- the Hadibo faults that cross north-east through central Socotra and have been interpreted as an upper-plate/lower-plate transfer zone do not pass laterally offshore into an oceanic transform fault [17] (Fig. 5).

Thus the fracture zones show no structural continuity with transverse structures in the adjacent continental margins. This is also true for the many fracture

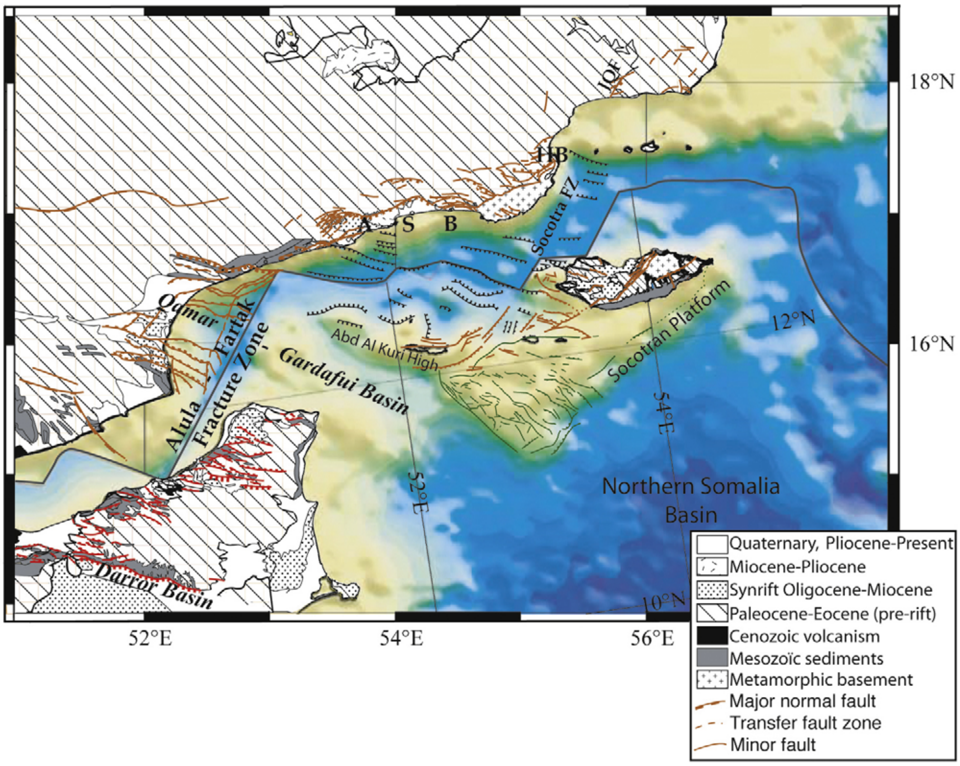

Fig. 5. Reconstruction of NE Africa to Arabia, by closing the oceanic crust and ''ocean-continent transition zone'' of the Gulf of Aden (modified after d'Acremont et al. [11]). Alula-Fartak is the largest offset transform fault and fracture zone in the Gulf, yet there are no strike-slip faults in its projection onshore, only WNW-trending normal faults. It formed after rifting, transecting across the middle of the pre-existing Qamar-Gardafui rift basin and the bordering Fartak-Alula horst high to the south (d'Acremont et al. [11]), Bellahsan et al. [4]). ASB = Ashawq-Salalah Basins; HB = Hasik Basin, JQF = Jabal Qarabiyan Fault, Faille (Fr.).

Fig. 5. Reconstitution depuis le Nord-Est de l'Afrique jusqu'à l'Arabie, par fermeture de la croûte océanique et de la « zone de transition océan-continent » du golfe d'Aden (modifié d'après d'Acremont et al. [11]). Alula-Fratak est la plus grande faille transformante et zone de fracture, décalée, du Golfe, bien qu'il n'y ait aucun décrochement dans sa projection à terre, mais uniquement des failles normales de direction WNW. Elle se forme après le *rifting* traversant le centre du bassin de rift de Qamar-Gardafui et du horst de Fartak-Alula qui le borde haut vers le sud (d'Acremont et al. [11]), Bellahsan et al. [4]). ASB = bassins d'Ashawq-Salalah ; HB = bassin d'Hasik, JQF = Jabal Qarabiyan Fault, Faille (Fr.).

zones further west in the Gulf of Aden, which, like Alula-Fartak, cross en echelon overlapping rift basins and highs [14,15,28]. Furthermore, the far western Gulf of Aden (west of 45°E to the Gulf of Tadjoura) is like the western Woodlark Basin in that, where the formation of oceanic crust is just beginning (< 2 Ma), there are no transform faults at all – even, in this case, despite significant spreading obliquity [13]. This supports a scenario in which transform faults initiate after spreading has commenced.

The ~400-km long CRFZ (Fig. 6) off NW Australia is like the Alula-Fartak Fracture Zone in having no strike-slip faults onshore from its projection. It appears to have linked bounding rift structures on opposite sides of a very wide rifted region, such as occurs between the east and west rifts of East Africa today [35]. The CRFZ formed between seafloor spreading in the Cuvier Basin to the south and continued continental stretching and distributed magmatism within the Exmouth Plateau to the north. Reconstructions based on magnetic anomaly interpretation show that the ridge propagation event that completed continental break-up (i.e., fully separated the Exmouth Plateau and NW Australia from greater India) terminated the large-offset CRFZ [26]. Ridge propagation and jumping are common processes that reorganize oceanic ridge segmentation and orientation, and can create and destroy transform faults and non-transform offsets, as is also seen in the Woodlark Basin and on the Sheba Ridge [12,20,34].

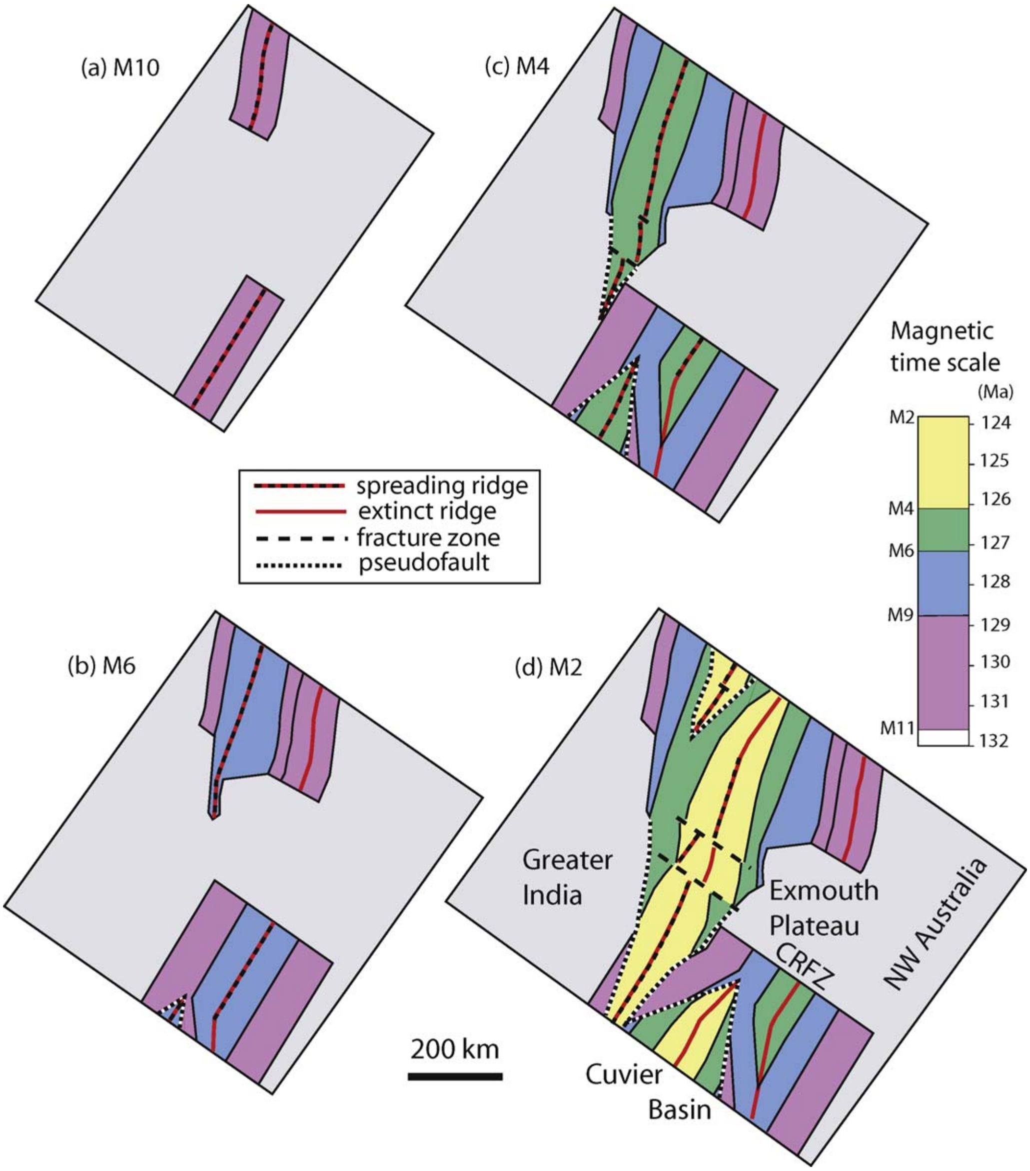

Fig. 6. Reconstruction of the separation between NW Australia and greater India, after Robb et al. [26]. Grey shaded areas are the deformed continental crust. Colored areas are oceanic crust formed by seafloor spreading at times given by the color scale. The Cape Range Fracture Zone (CRFZ) formed between seafloor spreading in the Cuvier Basin to the south and continued continental stretching and distributed magmatism within the Exmouth Plateau to the north. The ridge propagation event that completed continental break-up reorganized the spreading segmentation and removed the large CRFZ offset.

Fig. 6. Reconstitution de la séparation entre le Nord-Ouest de l'Australie et l'Inde, selon Robb et al. [26]. Les zones ombrées en gris représentent la croûte continentale déformée. Les zones colorées représentent la croûte océanique formée par accrétion aux temps donnés par l'échelle de couleur. La zone de fracture de Cape Range (CRFZ) s'est formée entre l'accrétion océanique dans le bassin de Cuvier au sud et l'étirement continental et l'activité magmatique au sein de Plateau Exmouth, au nord. L'événement de propagation de la dorsale qui complète la cassure continentale réorganise la segmentation d'expansion océanique et supprime le grand décalage CRFZ.

5. Conclusions

Spreading segments in the Woodlark Basin and in the $\sim 45^\circ$ obliquely opening Gulf of Aden show similar initiation characteristics, nucleating en echelon in overlapping rift basins. Transform faults did not develop until seafloor spreading began. Transforms (such as Moresby, Davies, Alula-Fartak, the initial Socotra and that to its east) were not inherited from transverse rift structures, although they did form before the conjugate margins were fully separated. In the process of linking two spreading segments that developed with ~70-km offset, the Moresby Transform truncated the tip of one segment within 0.5 million years of their spreading overlapping. The ~200-km-offset Alula-Fartak Fracture Zone transected across the middle of the pre-existing Qamar-Gardafui rift as well as the bordering Fartak-Alula horst [11]. At the western ends of the Woodlark Basin and the Gulf of Aden, where the formation of oceanic crust is just beginning (< 2 Ma) and spreading segments have little or no offset, transform faults have yet to form. The ~400-km-long CRFZ off NW Australia developed after seafloor spreading began in the Cuvier Basin but while the continent was still being stretched and intruded in the adjacent Exmouth Plateau [26]. In all three regions, the initial spreading center segmentation was modified by ridge jumps and/or propagation shortly after continental break-up. Early-formed transform faults terminate in oceanic crust or at the COB adjacent to sheared segments of conjugate continental margins; i.e., they formed as or after seafloor spreading began. Given that syn-rift accommodation zones are most commonly oblique features, and therefore unlikely precursors of transform faults, we expect this conclusion to have general validity beyond the specific cases presented here.

Acknowledgments

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